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Biological Effects of Air Pollution in the Sierra Nevada

Cahill and others (SNEP) have described the nature and extent of air pollution in the Sierra Nevada in another section of this report. The purpose of this section is to examine two topics of concern under the broad subject of biological effects of air pollutants in the Sierra Nevada. The first topic of primary concern is ozone transported to the western slope of the Sierra from upwind urban areas and its effect on sensitive tree species. The second topic is the simultaneous deposition and accumulation of nitrogen compounds in relation to ecosystem processes. The principal regions of concern are the middle and southern portions of the western slope of the Range because the combined pollutant loads from the San Francisco Bay Area and urban centers of the San Joaquin Valley present the maximum chronic exposure to ozone in this region. At present there is no such evidence of photochemical pollutant transport to eastern Sierra Nevada forests.

Annual measurements since 1991 of the crown health of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) and Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) from Lassen Volcanic National Park southward to Mountain Home State Park show an increasing level of chronic ozone injury from north to south. The amount injury is also influenced by the nearness of forest stands to the Valley, elevation and terrain position. Trees on upper slopes and ridge lines tend to show the most damage. Within stands the dominant and codominant trees are less injured than intermediate or suppressed trees which have more intense competition for light, water and nutrients. There is also a species difference in ozone sensitivity.

Ponderosa and Jeffrey pine are the most sensitive species to ozone and accumulated needle injury is easily detectable on older needle whorls as a chlorotic mottle. On the other hand black oak (*Quercus kellogii*) shows injury symptoms to foliage only in years with abundant soil moisture and average ozone exposure. The decreasing order of sensitivity for other conifers is white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*) and, sugar pine (*P. lambertiana*). Foliage symptoms are rarely seen on these

species in the Sierras. The chronic ozone injury to ponderosa and Jeffrey pine interacts with other stresses, in particular periodic drought, to make them more vulnerable to bark beetle attack.

Each drought year causes the length of needles formed in those years to be progressively shorter because water deficits diminish photosynthesis and limit growth. Low stomatal conductance in dry summers reduces ozone uptake and ozone injury. When the drought is broken the recovery from drought is hampered by the diminished surface area of photosynthetically active needle tissue in shorter one-year-old and older needle whorls formed during the drought. Even though the newest needles formed in the first growing season following a resumption of adequate precipitation attain a more nominal length, higher stomatal conductance increases ozone flux to old and new needles further diminishing the ability of sensitive trees to recover from the drought. Chronic ozone injury symptoms appear on older needle whorls and they drop to the forest floor. Ozone and drought interact to influence the competitive ability of ponderosa and Jeffrey pines in mixed conifer stands. The intensity of this interaction is related to frequency of 2-3 year drought periods.

Fire exclusion favors the reproduction and growth of white fir and incense cedar and limits the regeneration of ponderosa and Jeffrey pine because the latter require a mineral seedbed to become established. Further reductions in competitive ability of ponderosa and Jeffrey pines due to ozone stress, exacerbates the conversion to stands with more fir and cedar. The development of live fuel ladders of understory fir and cedar which may lead to a higher frequency of destructive crown fires, i.e., old growth trees of all species of species are more likely to be eliminated.

If present concentrations of ozone persist for many years into the future the Sequoia-Kings Canyon National Park (SEKI) and the Sequoia National Forest (SNF) will be the most affected regions. The rate of decline in dominance of ozone-injured ponderosa and Jeffrey pine will depend upon the frequency of droughts and associated bark beetle-caused mortality. Because there is a wide range of ozone sensitivity within these species the effect will be selection for those genotypes which are more resistant to ozone, and a loss of within-species diversity.

If ozone air quality improves it is expected that the crown condition (vigor) of ponderosa and Jeffrey pines will improve as shown in the San Bernardino National Forest (SBNF) between 1974 and 1989. If ozone air quality worsens the level of tree injury now present in SEKI and SNF will spread northward. Conditions will worsen in SEKI and SNF. Managed forests may require repeated salvage cuts as happened in the SBNF in the 1960's and 1970's.

Another potential biological effect of air pollution is the dry deposition of nitrogen to forests. Nitrogen is present in photochemical smog along with ozone in the form of nitric acid and nitrogen dioxide gases, and fine particles comprised of nitrate and ammonium salts. Direct effects on foliage are not present as a result of exposure but nitrogen accumulated from dry deposition has been shown to increase the rate of litter decomposition and in the most polluted portions of the SBNF a state of nitrogen saturation may exist today. The nitrogen content of water from watersheds in the San Gabriel mountains exceeds Federal standards for drinking water. The Sierra Nevada is still a sink for nitrogen deposited from the atmosphere but a combination of time and increased deposition rates may lead to altered nutrient cycling and eventually nitrogen saturation.

Literature Review

Western Slope of the Sierra Nevada Mountains

Air quality issues for the Sierra Nevada have been referred to in the context of effects on air quality related values in Wilderness because of the stipulations of the Clean Air Act and 1977 Amendments. Peterson and others (1993) have provided a guide for evaluating effects on air quality related values in Sierra Nevada Class I Wilderness areas. The purpose of this review is to examine air pollution effects for west-side ecosystems without respect to Clean Air Act designation.

Detection of ozone injury symptoms to ponderosa and Jeffrey pines in the Sierra Nevada (Miller and Millecan 1971) and subsequent surveys by the USDA, Forest Service, Forest Pest Management using 52 trend plots (Pronos and Vogler 1981, Allison 1982, 1984a, 1984b) provided the earliest data describing the extent of ozone, injury and the early trends of the severity of injury. For example, Pronos and Vogler (1981) reported that between 1977 and 1980 the general trend was an increase in the amount of ozone symptoms present on pine foliage. Peterson and others (1991) sampled crown condition and derived basal area growth trends from cores collected from ponderosa pines at sites in seven Federal administrative units (National Forests and National Parks) located from north to south in the Sierra Nevada including Tahoe National Forest, Eldorado National Forest, Stanislaus National Forest, Yosemite National Park, Sierra National Forest, Sequoia-Kings Canyon National Park, and Sequoia National Forest. In July-August 1987, four symptomatic and four asymptomatic sites were visited in each unit and only sites with ponderosa pines greater than 50 yr old were selected for sampling. The symptomatic plots generally indicated increasing levels of chronic ozone injury (reduced numbers of annual needle whorls retained and chlorotic mottle symptoms on younger age

classes of needles) from north to south.

Peterson and others (1991) documented the regional nature of the ozone pollution problem originating primarily from the San Joaquin Valley Air Basin (SJVAB), as well as the San Francisco Bay Air Basin further to the west. The study found no evidence of recent large-scale growth changes in ponderosa pine in the Sierra Nevada mountains; however the frequency of trees with recent declines of growth did increase in the southernmost units. Since these units have the highest levels of ozone (and more chlorotic mottle symptoms on needles of younger age classes) it was postulated from the weight of the evidence that ozone is one of the contributing factors to decline in basal area growth. Other factors limiting tree growth in this region include periodic drought, brush competition and high levels of tree stocking.

Another tree ring analysis and crown injury study was focused on Jeffrey pines in Sequoia-Kings Canyon National Park (Peterson and others 1989). This study suggested that decreases of radial growth of large, dominant Jeffrey pines growing on xeric sites (thin soils, low moisture holding capacity) and exposed to direct upslope transport of ozone, amounted to as much as 11 percent less in recent years relative to adjacent trees without symptoms.

Both permanent plots and cruise surveys have been employed in Sequoia, Kings Canyon (SEKI) (Wallner and Fong 1982 ; Warner and others 1982, and Yosemite (YOSE) National Parks to determine the spatial distribution and temporal changes of injury to ponderosa and Jeffrey pine within the Parks (Duriscoe and Stolte 1989). Comparisons of the same trees at 28 plots between 1980-82 and 1984-85 in SEKI showed increases of ozone injury to many trees and increases of the total number of trees with ozone injury. Ozone injury was found to decrease with increasing elevation of plots. The highest levels of tree injury in the Marble Fork drainage of the Kaweah River at approximately 1800 m elevation were associated with hourly averages of ozone frequently peaking at 80 to 100 ppb, but seldom exceeding 120 ppb.

A cruise survey in 1986 evaluated 3120 ponderosa or Jeffrey pines in SEKI and YOSE for ozone injury (Duriscoe and Stolte 1989) . More than one-third of these trees were found to have some level of chlorotic mottle. At SEKI symptomatic trees comprised 39% of the sample (574 out of 1470) and at YOSE they comprised 29% (479 out of 1650). Ponderosa pines were generally more severely injured than Jeffrey pines. The Forest Pest Management (FPM) score (low score equals high injury) was 3.09 for ponderosa and 3.62 for Jeffrey (Pronos and others 1978). These cruise surveys identified the spatial distribution of injury in SEKI and YOSE, and indicated trees in drainages nearest

the San Joaquin Valley were most injured.

In SEKI field plot observations of seedling health and mortality in natural giant sequoia (*Sequoiadendron giganteum* Bucch.) groves from 1983 to 1986 showed that emergent seedlings in moist microhabitats had ozone-induced foliar symptoms. Seedling numbers were reduced drastically from drought and other abiotic factors during this period (Miller and others 1994). A variable such as ozone that could injure seedling foliage sufficiently to reduce root growth immediately after germination could increase vulnerability to late summer drought. Following fumigation giant sequoia seedlings developed chlorotic mottle following exposure to both ambient ozone concentrations and 1.5 X ambient ozone in open top chambers during the 8-10 weeks following germination (Miller and others 1994). Significant differences in light compensation point, net assimilation at light saturation, and dark respiration were found between seedlings in charcoal filtered air treatments and 1.5 X ambient ozone treatments (Grulke and others 1989). One interpretation of these results is that ozone has the potential to be a new selection pressure during the regeneration phase of giant sequoia, possibly reducing genetic diversity.

The Lake Tahoe Basin is located at the northern end of the Sierra Nevada sampling transect (near the Eldorado National Forest) (Peterson and others 1991). Because it is an isolated air basin the air quality situation is distinct from other Sierra Nevada sites, and air pollution trends there are likely to be more related to local control measures and less to regional (SJVAB) measures. In 1987 a survey of 24 randomly selected plots in the basin included a total of 360 trees of which 105 (29.2 %) had some level of foliar injury (Pedersen 1989). Seventeen of these plots had FPM injury scores (Pronos and others 1978) that fell in the slight injury category. Of 190 trees in 16 cruise plots that extended observations to the east outside the basin, 21.6 % had injury--less than in the basin.

The Forest Ozone Response Study (FOREST)

Ozone injury index (OII) Changes by General Location and by Individual Plot Between Years from 1991 to 1993.

Annually since 1991 the ozone injury has been determined for 1700 trees in approximately 33 individual plots located from Lassen Volcanic National Park in the northern Sierra Nevada to Mountain Home State Park in the southern Sierra Nevada, including three plots in the SBNF by the FOREST interagency task group (Guthrey and others 1993 and 1994).

Changes in the calculated ozone injury index (OII) between years for the 1991 to 1993 period are represented as means for

about 50 trees in each of three plots at each location in Table 1. Trees that died during this period were not included in the comparison. A higher mean value indicates more injury since the index varies for 0 (no injury from ozone) to 100 (the most severe ozone injury). So far the actual range of OII observations is from 5.4 at Lassen Volcanic National Park to 65.7 in the western district of the San Bernardino National Forest. The subjective meaning of these OII values is a trace of injury or very slight injury at Lassen Volcanic National to a high moderate or low severe amount of injury at the San Bernardino site (Schilling and others 1995).

To evaluate the OII changes between 1991 and 1993, the paired t-test was used to determine if changes were significant (Table 1). All t-statistics are presented and a t-value of at least .05 or smaller was judged to be necessary before significant differences could be claimed. Accordingly, the majority of changes between 1991-1992 and 1992-1993 were decreases indicating some improvement in crown condition. The exceptions in 1991-1992 were Jerseydale and Barton Flats which both increased slightly. In 1992-1993 only Mountain Home State Park showed an increase compared to five sites with no change and six sites with a decrease in OII. Mather and Wawona in Yosemite (YOSE) had low OII scores in 1991 and have continued to decrease in the last two years.

Table 1. OII Changes from 1991 to 1993 at 33 Sierra Nevada Plots Listed in North to South Order and Three San Bernardino Mountain Pine Plots.

Plot Name	1991 Mean	t stat.	1992 Mean	t stat.	1993 Mean
Manzan. Lake (LV)	---	---	2	.03	1 (-)
WhiteCloud	15	.18	14	.95	14
Sly Park	18	.29	16	.04	14 (-)
5 mi LC	16	.06	14 (-)	.31	15
Mather (YOSE)	11	.03	8 (-)	.002	5 (-)
Jersey Dale	15	.0005	22 (+)	.51	23
Wawona (YOSE)	12	.08	10	0	3 (-)
Shaver Lake	9	.78	10	.22	11
Grant Gr. (SEKI)	26	.02	24 (-)	.27	23
Giant For. (SEKI)	29	0	25 (-)	.01	23 (-)
Mtn. Home	21	0	13 (-)	0	18 (+)
Barton Flats	29	0	34 (+)	.01	32 (-)

Annual Changes in the Proportion of Trees with Ozone Injury Symptoms at Each Location From 1991 to 1993.

The smallest proportion of symptomatic trees was seen at Manzanita Lake (.187) and the most at Barton Flats (1.00), using 1993 data as an example (Table 2). From year-to-year, significant decreases in numbers of trees at each location with ozone injury symptoms occurred at Mather, Wawona, and Mountain Home in 1992 and Wawona in 1993. Increases were seen at Jerseydale in 1992 and Mountain Home in 1993. The stability of this count at most plots is the prevailing condition.

Table 2. Changes in proportion of trees with foliar symptoms of ozone in 1991, 1992, and 1993 at Sierra Nevada and San Bernardino Mountain Pine Plots.

Location Name	1991 Mean	t stat.	1992 Mean	t stat.	1993 Mean
Manzan. Lake (LV)	---	---	.200	.29	.187
WhiteCloud	.701	.47	.673	.49	.653
Sly Park	.628	.39	.590	.37	.533
5 mi LC	.620	.87	.624	.14	.678
Mather (YOSE)	.520	0	.300(-)	.78	.313
Jersey Dale	.538	.001	.742(+)	.10	.835
Wawona (YOSE)	.490	0	.317(-)	0	.159(-)
Shaver Lake	.514	.41	.469	.001	.655
Grant Gr. (SEKI)	.946	.74	.953	.08	.913
Giant For. (SEKI)	.924	.37	.903	.64	.890
Mtn. Home	.806	0	.535(-)	.0002	.721(+)
Barton Flats	.976	.32	.992	.08	1.000

Distribution of OII Across Crown Position Classes (CPC) for all Plots in 1993 and Changes of Ranking at all Locations in 1991-1993.

Table 3 shows that for one sample year, 1993, Dominant (D) and Open Grown (OG) trees have generally lower OII's than Co-Dominant (CD), Intermediate (I), and Suppressed (S) trees. Table 4 represents a larger aggregation of these data, a summary of 1991, 1992 and 1993 which also shows significant differences in OII between crown position classes but changes in the ranking from year to year.

Table 3. Average OII in 1993 in relation to crown position class, including all trees in all plots.

	Crown Position Class				
	D	CD	I	S	OG
Number of Trees	308	661	500	105	110
Average OII	10.50	15.50	16.80	15.54	11.55

Table 4. Ranking of OII in Relation to Crown Position Class (CPC) in 1991, 1992 and 1993 at all plots.

CPC	1991		CPC	1992		CPC	1993	
OG	14.35	a	D	12.05	a	D	10.50	a
D	15.45	a	OG	12.20	ab	OG	11.55	ab
S	17.59	ab	S	14.25	abc	CD	15.50	bc
CD	17.79	ab	CD	17.07	bc	S	15.54	bc
I	19.57	b	I	18.57	c	I	16.80	bc

Effects of Pollutant Mixtures

The California Air Resources Board has published annual summaries of research sponsored by the Board to assess acidic deposition effects in the Sierra Nevada (California Air Resources Board 1983,1994) in compliance with two consecutive programs approved by the State legislature. A major theme of this work is the assessment of wet and dry deposition of sulfur and nitrogen species and their effects on geologic substrates (rocks and soils), surface waters, and aquatic biota. Critical assessments of this major body of research are in progress by subject matter experts. This task is enormous and complex. This important work will be published by the California Air Resources and will be a much more comprehensive product than could be attempted in the present document, however, the following paragraphs will discuss some research that relates to direct effects of sulfur and nitrogen compounds on the foliage of pines, and on possible accumulative effects on the mixed conifer ecosystems of the Sierra Nevada.

Investigations of the possible combined effects of sulfur dioxide and ozone were completed in the region just northeast of Bakersfield in a two-year period (Taylor and others 1986). Both ozone and sulfur dioxide were measured continuously at Bakersfield (Oildale), at Democrat Springs, Fire Guard Station in the lower Kern Canyon (oak woodland) and at Shirley Meadow (mixed conifer forest). Daily ozone peaks at Bakersfield and Shirley Meadow were similar in magnitude but sulfur dioxide was never detectable at Shirley Meadow and only detectable on rare occasions at Democrat Springs. Sulfate levels in pine needle tissue was not elevated at Shirley Meadow and there was no evidence to suggest anything except ozone injury to foliage of sensitive ponderosa and Jeffrey pines. Controlled fumigations of pine seedlings in open-top chambers using mixtures of ozone and sulfur dioxide did indicate an enhancement of foliar injury by the mixture of ozone and sulfur dioxide.

Seedling exposures to simulated acid rain and ozone were carried out with ponderosa pine for a three year period at Whitaker Forest, an experimental site in the southern Sierra Nevada. This experiment was part of the Electric Power Research Institute research program entitled: Response of Plants to Integrated Stress (ROPIS). The experimental design included acid rain (pH 3.5, 4.4, 5.3), ozone (CF, NF, NF150, AA), two levels of dry deposition (90 % and 60% filtration), and two levels of soil moisture availability (adequate and drought stressed). After 2 consecutive years of exposure the preliminary results suggested no effect from acid rain treatments, a much greater effect of ozone on adequately watered seedlings, and an interaction between 60% particle filtration and ozone resulting in more ozone injury (Temple and others 1992).

These results appear to be consistent with the appearance of mature ponderosa pines near the Whitaker Forest site, but seedling responses can not be offered as a complete substitute for data from mature trees. Seedlings are characterized by higher physiological rates and higher growth rates than mature trees.

Accumulative Effects of Nitrogen on Ecosystem Processes

Although there is an absence of direct effects of wet or dry acidic deposition on foliage and above-ground processes there is still the possibility that a gradual degradation of forest ecosystems may be developing through cumulative impacts on soils. Mechanisms for cumulative impact may include accelerated soil acidification (Reuss and Johnson, 1986), trace metal accumulation (Smith, 1990), and nitrogen saturation (Aber et al 1989). The nitrogen saturation hypothesis will be discussed in greater detail because nitrogen accumulation appears to be a distinct characteristic of California wildlands, which are traditionally nitrogen-limited, exposed to photochemical smog.

A detailed study of the gaseous and particulate species of sulfur and nitrogen was done in a rural area in the Kern River Canyon east of Bakersfield, and two urban areas including Martinez and San Jose (John, et al, 1984). The oxides of nitrogen were present at higher concentrations than sulfur oxides at all sites. Levels of NO_3^- and NH_4^+ washed from foliage and litter of ponderosa and Jeffrey pines at ten sites across an O_3 gradient in the San Bernardino mountains were highly correlated (R=0.73 to 0.82) with average hourly ozone concentrations. Deposition of sulfur also followed the same pattern (Fenn and Bytnerowicz 1993).

The nitrogen content of ponderosa pine litter was positively correlated with litter decomposition rates in the SBNF (Fenn and Dunn 1989). The same was true of litter decomposition rates of sugar pine and incense cedar; also, ponderosa pine foliage exhibiting severe ozone damage at high pollution plots abscised 2-4 years earlier than foliage from low pollution plots. Nitrogen availability in the litter layer is affected indirectly by the rate of ozone-induced litter fall, as well as the nitrogen content of needle tissue. The amount of litter fall was greatest from trees with moderate amounts of crown injury (Arkly and Glauser 1980), as compared to severely injured and uninjured trees. Therefore, the total amount of nitrogen varies with litter depth and can be expected to be quite variable over the landscape depending on amounts of crown injury from tree to tree. From ozone injured trees the litter has a higher proportion of needles from younger whorls inherently higher in nitrogen content (and lower in Ca content). This undoubtedly contributes to the increased nitrogen content of litter at plots in the western

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portions of the San Bernardino mountains (Fenn and Dunn 1989).

The continued accumulation of nitrogen in forest ecosystems, leading to nitrogen saturation, has important ecological effects including: soil acidification, cation depletion due to excess nitrate and cation leaching losses, nutrient imbalances, changes in plant communities as a result of the competitive advantage of nitrophilous species, decreased mycorrhizal symbiosis and increased drought stress (Aber and others 1989, Schulze 1989, Skeffington and Wilson 1988). Decreased run-off water quality due to high nitrate concentrations is another product of nitrogen saturation already demonstrated in Europe (Hauhs and others 1989), the eastern United States (Stoddard 1994), and in stream-flow from the San Gabriel mountains in southern California (Riggan and others 1985).

Summary

An assessment of the impact of air pollution on Sierra Nevada, west-side mixed conifer forests includes both the present evidence for chronic injury to sensitive species by ozone, and the possible accumulative effects of nitrogen deposition from the atmosphere. The reaction of ponderosa and Jeffrey pines and companion species in the mixed conifer type to ozone and nitrogen deposition is determined by complex interactions of both abiotic and biotic disturbance elements. In the future it is necessary to include climate warming as one of the driving variables.

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